BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION

In the Matter of	) ET Docket No. 04-186
Unlicensed Operation in the TV Broadcast	)
Bands	)
	) ET Docket No. 02-380
Additional Spectrum for Unlicensed Devices	)
Below 900 MHz and in the 3 GHz Band	)

REPLY COMMENTS OF

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Enabling and Evaluating
Unlicensed Operation in the TV Broadcast Bands

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1. Introduction

In the FCC 04-186 proceedings discussing the notice of proposed rulemaking, Unlicensed Operation in the TV Broadcast Bands,[2] the commenters question what criterion should be used to evaluate the impact of unlicensed devices operating in the TV broadcast bands. Many comments make worst-case assumptions to show that unlicensed devices could have a negative impact on licensed devices. The FCC has a long-standing notion of "harmful interference", but this is not precisely defined and is mainly used in a context of evaluating existing interference. This document makes three contributions to this discourse:

1. A conceptual notion of harmful interference is developed. Interference is harmful if it increases the unavailability of the licensed services. The question is by how much. A standard used in other FCC proceedings defines an increase in unavailability of 10% as harmful. Though, somewhat arbitrary, an increase of 10% is small relative to the year-to-year variability in unavailability and unlikely to be considered significant[3]. Licensed service availability is estimated at 99.9%, so harmful interference as defined in this document is when unavailability increases by 0.01% (1 in 10,000).

2. An interference model is developed around this notion. The model computes the fraction of licensed devices made unavailable because of unlicensed operation. It considers factors such as the type of unlicensed signal modulation, antennas, ability to detect active licensed channels, power control, and activity levels of the licensed and unlicensed devices. Examples using the model suggest that the small increase in interference allowed by the harmful interference definition above supports unlicensed device densities over 1,000 unlicensed devices per square kilometer. A high density apartment building example is also analyzed. It is found that there are mitigating

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[2] Notice of Proposed Rule Making, Unlicensed Operation in the TV Broadcast Bands, FCC 04-186 Released May 25, 2004.

[3] As recommended in the NPRM, channels with public safety and other concerns (2-4, 14-20, 37, and 52-69) should be excluded.

factors in this case that supports over 20,000 unlicensed devices per square kilometer without causing harmful interference.

3. Methods of avoiding licensed channels are assessed. Some commenters object that channel database methods may be unreliable. Database reliability can be greatly facilitated if the data entries are proactive and announce current and future channel usages. Commenters noted that methods that detect licensed transmitters or beacons sent by licensed transmitters have an inherent mismatch in beacon coverage and the location of licensed service receivers. Further, it beacons everywhere a channel might be used and not where it is actually used. An alternative approach is suggested that would use low-cost, low-power beacons at licensed device receivers in order to reliably announce the presence of licensed operation. This solution can be designed so that (a) it accurately predicts interference between the licensed receiver and the unlicensed transmitter, (b) beacons only indicate channels that are being used when they are used, and (c) it greatly simplifies incorporating reliable channel avoidance into every unlicensed device.

2. Detailed Analysis

The ideas introduced above are developed in more detail in the following sections.

2.1 A Standard for Harmful Interference

For the licensed operator, interference from unlicensed devices is unavoidable since both intentional and unintentional radiators can produce radio frequency power in the licensed band. This unwanted power can impact licensed performance in the worst case if the unlicensed source is placed sufficiently close to the licensed receiver antenna.[4] The FCC has recognized that assuming a worst-case interference regime will not maximize the social benefit of the spectrum.[5] The Spectrum Policy Task Force concluded that for unlicensed devices, "Using typical worst case predictive interference models would significantly reduce the potential of these devices to operate."[6] Licensed devices always have the potential of degraded performance from unlicensed devices. Yet, in practice most licensed devices work well. This suggests that the harmful interference of unlicensed devices should be measured according to their impact in practice.

In the Multichannel Video Distribution and Data Service (MVDDS) proceedings[7] the FCC reiterated that "impacting some existing customers of a service to an extent that did

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[4] For instance operating a power saw or drill near a TV or radio readily produces strong "static".

[5] Margie, Paul. *Efficiency, Predictability and the Need for an Improved Interference Standard at the FCC*. Telecommunications Policy Research Conference (TPRC) Arlington, VA, Sept. 19, 2003 He provides several examples that illustrate this point. (http://tprc.org/papers/2003/214/HarmfulInterference.pdf)

[6] *Spectrum Policy Task Force Report*, ET Docket No. 02-135. November 2002. pg. 13. (http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf)

[7] In Re Amendment of Parts 2 and 25 of the Commission's Rules to Permit Operation of NGSO FSS Systems Co-Frequency with GSO and Terrestrial Systems in the Ku-Band Frequency Range; Amendment of the Commission's Rules to Authorize Subsidiary Terrestrial Use of the 12.2-12.7 GHz Band by Direct Broadcast Satellite Licensees and Their Affiliates; and Applications of Broadwave USA, PDC Broadband Corporation, and Satellite Receivers, Ltd. to Provide A Fixed Service in the 12.2-12.7 GHz Band, *Memorandum Opinion and Order and Second Report and Order*, 17 FCC Rcd. 9614 (2002) (hereinafter *MVDDS MO&O and Second R&O*). (http://wireless.fcc.gov/auctions/53/releases/fc020116.pdf)

not rise to the level of harmful interference was outweighed by the benefits of adding new services or capabilities to a frequency band."[8] In the proceedings, the FCC set operational parameters based on a criterion that MVDSS does not increases the baseline DBS outage rate by more than ten percent per year. This requirement is interpreted as an average standard and not for each individual receiver.[9] "The ten percent benchmark represents an insubstantial amount of increased unavailability and does not approach a level that could be considered harmful interference."[10] In this way the FCC set a standard that it deemed as conservative for the existing licensed operators while providing entry for other services.

This suggests that a similar standard can be applied to unlicensed devices in the TV broadcast bands. Broadcast TV availability is not monitored by regulators but even if it were 100% available, other factors would limit its use by TV receivers. For instance, the availability of power from utilities varies (between utilities and from year to year) between 99.9% and 99.99%,[11] and so receivers must be unavailable for use for 0.1% to 0.01% of the time. Digital Broadcast Satellite service is similar to TV and is considered "extremely reliable with typical service availabilities on the order of 99.8 to 99.9 percent."[12] Broadcast TV coverage is defined by the $F(50,90)$ curves which nominally provides 90% service availability at the edge of each stations service.[13] When considering new higher power operation, broadcasters advocated "that a *de minimis* standard for permissible new interference is needed to provide flexibility for broadcasters in the implementation of DTV."[14] They argue that a 2% absolute increase in interference between TV stations is acceptable. This data collectively suggests that 99.9% is a conservative upper bound on the availability of broadcast service. This bound with the above FCC MVDSS 10% standard suggests a standard for the broadcast TV bands of no more than 0.01% (1 in 10,000) TV's can be adversely affected by the unlicensed devices on average. Given the range of availability values and the small fraction that results, this value is small in both a relative and absolute sense and exercises an abundance of caution.

2.2 A Model for Estimating Interference

The definition of harmful interference in the previous section requires some method to estimate the fraction of licensed devices that are unavailable to use because of unlicensed devices. This section contributes a model of the impact of unlicensed devices

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[8] *MVDDS MO&O and Second R&O*, at para. 32
[9] *MVDDS MO&O and Second R&O*, at para. 84
[10] *MVDDS MO&O and Second R&O*, at para. 72
[11] *Electric System Reliability Annual Reports*, California Public Utilities Commission. January 24, 2005. (http://www.cpuc.ca.gov/static/industry/electric/reliability/reliability_reports.htm) These contain measures of the so-called SAIDI, minutes of sustained outages per customer per year. They range from 50 to 600 minutes per year or 99.99% to 99.9% reliability. Further within a single service provider, the SAIDI varies by large factors of at least two from year to year.
[12] *MVDDS MO&O and Second R&O*, at para. 67
[13] Advanced Television Systems and Their Impact upon the Existing Television Broadcast Service. FCC 87-268. Fifth Report and Order. Released April 21, 1997. Appendix A, "Rule Changes", Part 73.625, (a).
[14] Advanced Television Systems and Their Impact upon the Existing Television Broadcast Service. FCC 87-268. Memorandum Opinion and Order on Reconsideration of the Sixth Report and Order. Released February 23, 1998. at para. 79.

that enables uniform comparison and evaluation of the unlicensed devices. It does not promote any particular approach but does provide a framework for discussing and comparing each approach's performance.

The model predicts the expected fraction of licensed receivers disrupted over a broadcast coverage area. A single unlicensed device, if properly designed, will not have wide impact on licensed usage across a coverage area. It is when the number of devices grows that the impact becomes significant. The model is a tool to show what is required for a high-density unlicensed device deployment (e.g., 1000 devices per square kilometer) to avoid harmful interference.

2.2.1 Model Summary

Mathematically, the model consists of a series of factors that account for the different elements that influence the number of disrupted licensed devices:

$$F = r_{\min}^2 PCEG_{UL} G_L MN_{UL} / A$$

where

F is the expected fraction of licensed devices with service disrupted.

$r_{\min}$ is the minimum separation between the unlicensed and licensed device in order to prevent the unlicensed device from interfering with the licensed device under typical operating conditions for the unlicensed and licensed device near the boundary of the broadcast coverage area. This is done under worst case conditions of the licensed device transmitting at maximum power on the same channel as the licensed device with both devices antennas pointing at each other.

P accounts for the use of power control by the unlicensed device. $P \le 1$.

C accounts for the ability of the device to avoid communicating on the same and adjacent channels as the licensed device. $C \le 1$.

E is the fraction of devices on and eligible to interfere with each other $E \le 1$.

G_{UL} accounts for the antenna gain pattern of the unlicensed device. $G_{UL} \le 1$.

G_L accounts for the antenna gain pattern of the licensed device. $G_L \le 1$.

M captures all the model constants. A typical value is $M = 2.9$.

N_{UL} is the number of unlicensed devices in the area.

A is the size of the area.

Most of the factors are less than or equal to one. In some cases they are very small. Worst case analysis of viewing only $r_{\min}$ would be overly pessimistic. The last four factors are outside the influence of the unlicensed device designer. But the first five factors can be affected by the unlicensed device design. Different modulation techniques, maximum transmit power, etc. can all affect $r_{\min}$. The sophistication of power control algorithms affects P. The fidelity of channel detection techniques strongly affects C. The level of device activity affects E. The unlicensed device's antenna affects G_{UL}. Technical readers are encouraged to read the model details in the appendix as important assumptions and derivations are presented there. Less technical readers may safely go to the next section.

2.2.2 Examples

To help interpret the model we give several examples. We emphasize that the examples and the numbers used are purely illustrative. For all the examples we will use a broadcast coverage area of 10,000km^2 which corresponds to a 56km (34mile) circle of broadcast coverage. We also use N_{UL} = 10,000,000 devices. This yields a N_{UL}/A of 1000 devices/km^2. This represents a large number of unlicensed devices deployed over a metropolitan area. The broadcast pathloss exponent is $a = 2$ and joint shadow fading is $\sigma = 7$dB.

Consider a low power device operating under the following conditions: r_{min} = 100m; the unlicensed devices have an omnidirectional antenna; the licensed antennas are approximated by 60 degree ideal sectorized antennas; the pathloss exponent for low-power devices is $b = 4$; and power is controlled uniformly over a log scale between max power and 20dB below max power. The fraction of: unlicensed turned on is 25%; licensed devices turned on. is 25%; and licensed devices listening to broadcast channels is 25%. As a reference, we consider the worst case that the licensed device is using a random channel. In this case, $P = 0.39$; $C = 0.02$; $E = 0.016$; $G_{UL} = 1$; $G_L = 0.17$; and $M = 2.9$. Combining these factors yields an expected fraction of disrupted devices of about 6/10,000. This suggests that even limited additional work to avoid using known TV channels would reduce the expected number of disrupted devices to an insignificant level. For instance if the unlicensed device could determine the presence of and avoid licensed broadcast channels (and adjacent channels) 90% of the time and the remaining 10% of the time the channel choice is random, then $C = 0.0022$, and the number of disrupted devices is less than 1/10,000. We emphasize that these number are across a major metropolitan area with ten million unlicensed devices. A suburban or rural area which we might expect to have factors of 10 to 1000 lower device density would have similarly reduced fraction of disrupted devices. For example a rural area with 100 devices per square kilometer would have a fraction of disrupted devices less than 1/10,000 even if the unlicensed devices chose channels randomly.

Consider next a high-power device operating under the same conditions as for the low power device except that: r_{min} = 10km; the unlicensed antennas are high-gain 30 degree sectors; $b = 2$; the fraction of unlicensed devices turned on is 50%; and again random channel selection. In this case, $P = 0.21$; $C = 0.02$; $E = 0.031$; $G_{UL} = 0.083$; $G_L = 0.17$; and $M = 5.8$. Combining these factors yields an expected fraction of disrupted devices of close to 1. This implies the unlicensed devices must be much more reliable in detecting and avoiding broadcast channels. For instance, if the licensed channel could be detected and avoided 99.99% of the time (in error no more than 50 minutes per year) then, $C = 2.\text{x}10^{-6}$ and the expected fraction of disrupted devices less than 1/10,000. The same level could be achieved in a rural area if licensed channels could be detected 99.9% of the time (8 hours per year).

The greatest potential for interference exists in dense settings, for instance in apartment buildings where the effective density could be above 1000 devices per square kilometer. There are several mitigating factors in this case. Such buildings are more likely to have wired Internet access (i.e., less likely to be high-power unlicensed devices). Similarly, they are more likely to have cable TV. Such buildings are often in urban areas where broadcast signals are stronger and easier to detect. For low-power devices used within these apartments, the communication distances are likely much smaller and thus require less transmit power. Social factors should not be ignored either. If some neighbor is too loud, you can ask them to be quieter. Similarly, if a neighbor places a wireless device too close to your TV, you can ask them to move it.[15]

We can incorporate these factors into the model by assuming half as many licensed devices listening to broadcast channels, channel detection can be twice as accurate, the power is controlled uniformly over a log scale between 10dB below max power and 20dB below max power, and half of all potential disruptions can be solved by social means (i.e., $P = 0.19$; $C = 0.0012$; and $E = 0.0039$) would support in our illustrative examples more than 20,000 unlicensed devices per square kilometer without exceeding the harmful interference threshold.

2.3 Assessing Licensed Channel Avoidance

The NPRM suggests three methods for avoiding licensed channel usage: combine unlicensed device geolocation with a channel usage database; use dedicated beacon signals such as from broadcast stations; and directly detecting transmitted broadcast signals.[16] This section analyzes these alternatives.

2.3.1 Channel Usage Detection

The above examples (which again we emphasize are for illustrative purposes) suggest that the discussion in the comments on the problem of detecting broadcast channel usage is warranted as it is a key factor in preventing harmful interference. The standards for low-power devices are much lower than for the high-power devices. A low power device even with mildly accurate (90% or better) licensed channel detection and avoidance capabilities will avoid harmful interference for all but the most dense settings. The high-power devices as suggested by some commentators require much more reliable detection and avoidance capabilities. High-power devices are envisioned as being in fixed deployments which greatly eases meeting this requirement. In our illustrative example, we estimated that the unlicensed device would need to detect and avoid channels with an accuracy of 99.99%.

It should be noted that if a database approach is used, the database can have reliability and availability *less* than what is required for the unlicensed devices. The changes in such databases are infrequent. If the database were unavailable for even 24 hours, most high-power devices would have a stored record from before the database outage that would be accurate through the outage. High-power devices which would

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[15] General guidelines used in Part 15 rules development are (a) self-interference between two devices operated by the same household is not considered; and (b) between households a working assumption is 10m separation and wall attenuation of at least 10dB. The original NPRM, supra 2, footnote 50 reiterates this assumption. This suggests that some disrupting interference in such high density settings may not be considered harmful interference.

[16] NPRM, para. 20.

attempt to initialize during this period or otherwise did not have a valid record should not be allowed to operate.

The accuracy through outage periods would be improved if the databases incorporated new information proactively rather than reactively. For instance if a new channel will be used starting on a certain date, the database would include this information many days in advance so that unlicensed devices could plan and avoid the new channel even if the database is unavailable on the transition day. Similarly, Part 15.244 devices could enter planned event usages (time period and location) into the database well in advance. It would not be unreasonable for the database to be maintained so that information is valid over a future period (e.g., 48 hours). A query would enable an unlicensed device to operate over this period, even if the database was down at the moment the unlicensed device wished to operate. Fixed unlicensed devices which do not have a valid query would not be able to operate. Such a failsafe, "no database, no transmit" rule would be one way to provide a highly reliable approach to avoiding interference.

As a reference, consider the following high-power operation model. An operator wishes to provide broadband Internet access over a large area. A central radio base station is installed outdoors. The base station is connected to the Internet through a wired connection. At the time of installation or using an integral geolocation method, the radio estimates its location.[17] It makes a worst case assumption of its coverage area (i.e. an overestimate), queries the channel usage database over the Internet and assesses what channels it has available for operation. Meanwhile, radio transceivers are installed at customer premises. These radios, when turned on, passively scan and listen for the base station signal. This signal identifies valid uplink channels that can be used by the customer radio. The base station queries the channel database periodically (e.g., hourly) to ensure it has the latest information and adjusts beacon information accordingly. In this way, the customer radios can be kept simple and low-cost (technologically equivalent to a cellular telephone)[18] while providing licensed channel protection assurances.

2.3.2 Receiver Detection

Technically, unlicensed devices should detect and avoid licensed signal receivers since this is where interference takes place. Detecting the existence of licensed transmitters is only a proxy for detecting licensed receivers. Hence, much of the discussion in the comments that detecting broadcast transmitters (or beacons announcing such transmitters) will cover either too much or too little of the coverage area (i.e. the area where the transmitted signal is being received). Detecting receivers would have the advantages (a) nearby receivers could be detected regardless of transmitted signal levels; (b) broadcast channels could be used according to actual use rather than inferred use from detecting transmitted signals.

We see several methods for detecting receivers:

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[17] Such estimation does not necessarily have to be very precise. Errors of 100m or more would not significantly change the set of broadcast channels in use around an unlicensed device. If these errors were somehow thought to be significant, the unlicensed device can include these errors in its coverage estimates.
[18] Cellular telephones follow a similar base station access procedure.

1. The unlicensed device detects the LO signal emitted by a TV during reception.
2. The TV has a beacon attached that sends out a periodic pulse.
3. The TV has a device connected to the antenna input that detects the LO signal and then retransmits a beacon out the antenna path.

Every TV emits a carrier signal at the local oscillator (LO) frequency used during TV signal reception.[19] This signal is weak, but, can be used to detect the channel being received by a TV that is turned on and tuned to a specific channel.[20] Thus, if a LO detector could be incorporated into unlicensed devices, it would allow direct detection of receivers in the area and the channels that are being used. We performed some experiments in our lab to assess the potential of this detector.[21] Depending on the TV, the maximum LO detection range was found to vary from 3-15m.[22] This is likely only a fraction of the interference range of the unlicensed device. More sensitive techniques might yield further detection range but would require more measurement time and more expensive hardware that might be prohibitive for low-power unlicensed devices. The TV bands have many spurious signals that are similar to the LO signal and would yield many false positive detections.[23] Further this method does not work for devices other than TVs.

Receiver avoidance is more direct if the receiver has a dedicated beacon designed to turn on when the licensed receiver is turned on and announce the receiver's presence to unlicensed devices. The LO signal when measured directly at the antenna input was at most a weak -80dBm. A low-power tag could broadcast at a higher, but modest signal level such as -10dBm. This level would ensure a high probability of detecting nearby receivers.[24] The frequency and format of the beacon would need further definition.[25] It

[19] Robert D. Weller, et al., "New Measurements and Predictions of UHF Television Receiver Local Oscillator Radiation Interference," *Proceedings of the 2003 IEEE Broadcast Technology Society Symposium,* 2003.

[20] In the UK it is used to detect unregistered TV's. See the UK TV Licensing website. http://www.tvlicensing.co.uk/information/tvdetectorvans.jsp

[21] A procedure similar to that as reported by Weller, et al. supra 19. A TV was equipped with a rabbit ears antenna. An HP 8594E spectrum analyzer with a similar antenna was used as a detector with the settings:

Resolution BW	10 KHz
Video BW	1 KHz
Sweep time	50ms
Attenuation	0dB
Ref level	-30dBm

The signal detection sensitivity was -104dBm. Three TVs were tested, a 1991 Emerson 13", a 1991 Mitsbishi 24" TV, and a 2000 JVC 20" TV. The TVs were tuned to channel 11. The furthest distance where a LO signal could be seen above the noise floor was measured. Then the output of the TV was connected to a splitter that connected to the antenna and to a coax cable that was connected directly to the spectrum analyzer input. The antenna was required so the tuner would lock on to a broadcast station and the LO signal would stabilize. The power of the LO signal was measured on the spectrum analyzer.

[22] These measurements are consistent with Weller et al. supra 19.

[23] Private communication with Mark McHenry of Shared Spectrum.

[24] It is enough to detect any receiver using a channel to mark it as used. Interference is more likely when a licensed device is closer to the unlicensed device, but, beacon detection is also more likely. This implies that such a technique becomes more reliable in high-density scenarios exactly as is needed to avoid harmful interference.

[25] It is beyond the scope of this document to give specific beacon recommendations. One would expect that the beacon would be a) in a band within the TV bands or on a nearby band (e.g. the 433.050-434.790MHz

would be a simple engineering exercise to develop a low-cost design that would cost a few dollars at most.[26] Unlicensed devices would be required to listen for the beacons before they begin any transmissions and periodically afterwards. If heard, the unlicensed device would not operate. While straightforward, this approach has several flaws. First it signals the presence of the receiver at the receiver and not at the antenna which might be on the roof and highly directional. Second, it announces the presence of receivers even when they might be receiving cable TV, recorded programming or other non-broadcast signals. Third, it announces the presence of the receiver, but, not the channel used by the receiver.

The third approach combines the first two. A simple device can be built that is placed between the antenna cable and the receiver antenna input. This device can easily detect the LO oscillator and then send a low-power beacon out the antenna path. The beacon would be slightly more complex in that it would encode the channel used by the receiver. Like the beacon above, the engineering design would be straightforward, though the cost would be higher since it must detect the LO as well as broadcast the beacon. Since it sends the beacon along the same path followed by potential interference, it more accurately identifies the interference location (i.e., the receiver antenna). Unlicensed devices could operate in the vicinity of receivers with non-broadcast inputs since the low-power beacon signal is sent into a cable instead of the antenna and the beacon would not be detected by unlicensed devices.[27] Finally, the beacon announces directly the receiver channel and type. An unlicensed device would use the set of beacons that it receives to choose an unused channel. The concept can be applied to a variety of licensed devices. In the future, the device can also be incorporated directly into the licensed receiver (e.g., as part of the Tuner Mandate[28]). This would use the tuner control logic circuitry to command the beacon rather than the indirect LO detection and could be integrated into the existing circuitry at minimal cost.

Such a proactive beacon system would be an alternative to database or transmitter measurement methods. Its effect in the model is to set a small value for *C*, the channel avoidance parameter. It might prove even more reliable and does not depend on having Internet connectivity or an expensive signal detector for weak licensed signals. It would allow low power devices to use channels that are being used generally in an area, but, not in the immediate vicinity of the unlicensed device. It therefore would expand the possible applications of the unlicensed technology. Most TVs are connected to cable and so would not require such a device, and newer licensed devices can incorporate them into their design at modest cost.

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band used by active RFID tags) so that existing antennas can be used; b) low duty cycle so that collisions between different receiver beacons would be minimized; and c) low data rate since the information conveyed is minimal (e.g. channel used and type of receiver). These suggest a simple low-power radio device.

[26] The "few dollars" claim is based on looking at similar devices such as active RFID tags, which start at $4. Active RFID tags are a relatively new technology and prices are expected to drop as they mature.

[27] In the NAB comments they included a study that showed an unlicensed device could interfere with cable reception if the unlicensed device had a high-gain antenna that was sufficiently close to the cable. In this scenario, the beacon would be received by the unlicensed device and thus could be used to detect this situation.

[28] Review of the Commission's Rules and Policies Affecting the Conversion to Digital Television, FCC 00-39, Second Report and Order and Second Memorandum Opinion and Order, August 9, 2002.

3. Conclusion

The notion of harmful interference discussed in this comment is a starting point for assessing the affects of unlicensed operation in the TV broadcast bands. A model developed around this notion shows that high-power and low-power unlicensed devices can successfully coexist with licensed devices. The model estimates the fraction of licensed devices disrupted by the presence of the unlicensed devices. It incorporates a range of factors that can influence the final result. All of the factors can be easily estimated or directly measured. In particular, one of the most influential factors, r_{min}, could be measured through direct measurement. This suggests that a device compliance model can be developed based on factors inherent to the device. In other words, the definition of compliance could be defined in terms of a bound on r_{min} as measured in a lab.

Illustrative examples indicate high-power devices will need to pay special attention to how they choose transmit channels since they have a strong potential to interfere over a large area. The lengthy discussion in other comments on reliable procedures for avoiding active channels is warranted. The model here can contribute to this discussion by providing concrete guidelines on how reliable these procedures must be.

The examples show that low-power devices can be much less reliable in this procedure and yet have minimal impact on licensed devices. They are helped by being lower power and because they are envisioned as being used indoors or at ground level and thus the walls and clutter (as expressed by the larger pathloss exponent) provide more isolation. But, since the channel assessment procedure is likely to be more ad hoc its reliability may be more difficult to assess.

Because of their important role in the performance of licensed devices, the methods for avoiding unlicensed channels were assessed. It is noted that channel usage databases do *not* have to be very reliable for reliable licensed channel avoidance if they have accurate proactive data. An alternative method was suggested that would provide robust localized information for avoiding used broadcast channels. The method uses small low-cost beacons at licensed receivers which directly and effectively addresses the interference issue. The method would expand the set of applications for unlicensed devices and enable unlicensed operation using any channel that is not being used nearby.

The model suggests that licensed and unlicensed devices can coexist at densities exceeding 1000 unlicensed devices per square kilometer. When applied to a worst-case scenario of a high-density apartment building, it is found that densities over 20,000 devices per square kilometer can be supported. Further work is needed to fix the parameters of the model and to provide more accurate estimates.

In setting the notion of harmful interference, an abundance of caution was used; admitting increases in interference that are 200 times smaller than allowed by the broadcasters among themselves (i.e., 0.01%). It should be clear from the model that such extreme caution imposes direct and substantial penalties on the deployment of unlicensed devices. For instance, if increases in interference were admitted that were 10 times smaller than allowed by the broadcasters among themselves (i.e., 0.2%), the harmful interference standard would immediately support a 20 times higher unlicensed device density.[29] Therefore, the harmful interference standard in this paper should be considered a model and the specific interference level should be set with careful consideration.

I would welcome further discussion, comments, or questions on the issues raised in this document, the assumptions used, or application of the model.

4. Appendix: Model Details

4.1 Model Assumptions

The basic idea of the model is that licensed receivers and unlicensed devices will be spread over a large area such as a metropolitan or rural area. A conceptual notion is that this area consists of the area covered out to some maximum distance (such as to the Grade B contour of a typical broadcast station). The shape of this contour is not particularly important as long as it is reasonably compact. A key concept is $r_{\min}$, the minimum non-interfering distance separation between unlicensed transmitter and licensed receiver when the licensed device is transmitting at full power on the same channel as the receiver is listening and both devices antennas are pointed toward each other. This, of course, is the worst case situation and other factors come into play to mitigate this situation. It is precisely the point of this model to make these factors explicit so that the mitigating role of smart unlicensed devices can be expressed concretely.

The basic model makes the following assumptions:

1. Only two-dimensional scenarios are considered.
2. Received power at a licensed device from an unlicensed device transmitter is $P_{int} = K_{int}\, g_{UL}\, g_L\, P_{UL} S_{int}/r^b$, where K_{int} is a constant related to antenna heights, cable losses, and other constants; g_{UL} and g_L are the unlicensed and licensed device antenna gains along the path connecting them; P_{UL} is the transmit power; r is the separation between the unlicensed transmitter and licensed receiver; b is the pathloss exponent for signals between the unlicensed and licensed device; and S_{int} is the shadow fading factor representing the variation in received power due to terrain, clutter, and other environmental factors.[30]
3. Received power at a licensed device from a broadcast tower is $P_{sig} = K_{sig} S_{sig}/R^a$, where K_{sig} is a constant related to broadcast power, antenna heights, cable losses, etc.; R is the separation between the transmitter and receiver; a is the pathloss exponent between the transmitter and receiver; and S_{sig} is a shadow fading factor representing the variation in received power due to terrain, clutter, and other environmental factors. Note the specific effects for the broadcast power and antenna gains are not broken out as separate factors since they will likely be constants and not vary over time.

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[29] Or, it would ease the design challenge for the same density by a factor of 20. For instance, using the 0.2% standard in the illustrative example of a high-power device, the unlicensed devices would have to detect and avoid licensed devices 99.8% of the time (i.e., incorrect no more than 16.7 hours per year) instead of 99.99% of the time (i.e. incorrect no more than 50 minutes per year).

[30] The model for assumptions 1-5 is derived from standard texts such as Rappaport, T.S., *Wireless Communications Principles and Practice*, 2nd Ed. Prentice Hall, 2002. Ch. 3-5

4. The licensed device is disrupted if $P_{sig}/P_{int} < T$ for some defined threshold T. Note that this threshold depends on the nature of the interference signal, and whether it is in the same channel as the licensed receiver or another nearby channel. Combining the previous assumptions, $P_{sig}/P_{int} = K\, S\, r^b/(g_{UL}\, g_L\, P_{UL}\, R^a)$, where $K = K_{sig}/K_{int}$, and $S = S_{sig}/S_{int}$.
5. The shadow fading S is well modeled by a log-normal distribution (i.e. log S is normal) with log normal standard deviation σ. Note that if S_{sig} and S_{int} are both log normal with log-normal standard deviation σ_{sig} and σ_{int}, then their ratio is also log normal. In practice, S_{sig} and S_{int} are correlated. A TV in the basement will receive weaker signals from both the broadcaster and the unlicensed device. Thus, $\sigma^2 < \sigma_{sig}^2 + \sigma_{\mathrm{int}}^2$.
6. The licensed devices are uniformly distributed over the broadcast coverage area. The coverage area is a circle of radius R_B. The probability a device is within R of the center is $\frac{R^2}{R_B^2}$. Let A be the coverage area, N_L the number of unlicensed devices in this area, and N_L/A the average density of unlicensed devices. For simplicity, all broadcast channels have the same coverage area.
7. The unlicensed devices are uniformly distributed over the broadcast coverage area and the number of these devices is N_{UL}. The licensed and unlicensed device separation, r, is small relative to the radius of the broadcast coverage so that r is independent of R.
8. A device which is turned off can not disrupt or be disrupted. A licensed device not using the broadcast channel (e.g. using cable) can not be disrupted.
9. Unless otherwise stated, antennas have a uniform random azimuth orientation.

Some notes on these assumptions are in order. The limitation to two-dimensional does not apply well to built-up metropolitan areas such as New York City. It does apply to urban environments with few high-rise buildings and typical suburban and rural environments. Later work will expand this model to three-dimensional environments.

The pathloss exponent is allowed to differ for the unlicensed and broadcast transmitters. It is expected that the broadcast transmitter will be close to a free-space pathloss model ($a = 2$). The unlicensed device will differ depending on the device. For low-power devices without special antenna mounting, the pathloss will be closer to the two-ray ground model ($b = 4$). For higher power transmitters mounted on outdoor poles, it will be between 2 and 4 depending on antenna height and location.

Shadow fading can have log-normal standard deviations as large as 10dB for both S_{sig} and S_{int} suggesting a total of 14dB for the log normal standard deviation for their ratio. Because of correlations between them we might expect a total variation equal to half of this value or 7dB.

The uniform distribution of unlicensed devices suggests that the expected number of licensed devices in a ring of thickness dr and radius r from the unlicensed device is $2\pi r\, N_L/A\, dr$.

4.2 Model Derivation

There are three main random variables in this model. The distance of the licensed device to the broadcast transmitter, R; the distance from the licensed device to the unlicensed transmitter, r; and the shadow fading value S. Once these are accounted for, secondary random variables can be easily admitted.

We are interested in computing expected number of licensed devices disrupted by an unlicensed device. First we compute the expected number disrupted by a single unlicensed device and then scale to more than one unlicensed devices. Consider a single unlicensed device. Given r and S, a licensed device is disrupted if $\frac{P_{sig}}{P_{\text{int}}} = \frac{SKr^b}{g_{UL} g_L P_{UL} R^a} < T$, i.e. $R > \left(\frac{SKr^b}{g_{UL} g_L P_{UL} T}\right)^{1/a}$. T is the threshold given the current channels of the licensed and unlicensed devices; and the modulation scheme used by the unlicensed device. It follows from assumption 6:

$$\Pr\left\{R > \left(\frac{SKr^b}{g_{UL} g_L P_{UL} T}\right)^{1/a}\right\} = \begin{cases} 1 - \frac{1}{R_B^2}\left(\frac{SKr^b}{g_{UL} g_L P_{UL} T}\right)^{2/a} & \text{if } \left(\frac{SKr^b}{g_{UL} g_L P_{UL} T}\right)^{1/a} \le R_B \\ 0 & \text{otherwise} \end{cases}$$

The expected number of licensed radios at a distance r to $r + dr$ is $N_L/A \; 2\pi r \; dr$. To get the total expected users disrupted by the unlicensed device we integrate over all distances r, and for each r, over all possible S.

$$D = \int_0^\infty \int_0^\infty \frac{N_L}{A} 2\pi r \Pr\left\{R > \left(\frac{SKr^b}{g_{UL} g_L P_{UL} T}\right)^{1/a}\right\} p_S(s)\, drds$$

where p_S is the distribution of S. Switching the order of the integration and integrating yields:

$$D = \pi \frac{N_L}{A} \left(\frac{R_B^a g_{UL} g_L P_{UL} T}{K}\right)^{2/b} \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}} .$$

This is the expected number of licensed devices disrupted by a single unlicensed device. For N_{UL} unlicensed devices, we conservatively overestimate[31] the number of disrupted devices as simply N_{UL} times larger.

An alternate form to consider this equation is derived as follows. Consider the worst case when a licensed device is at the edge of the broadcast area, the unlicensed device is at maximum power on the same channel as the licensed device with both antennas pointing at their maximum gain towards each other. Let $S = 1$ and consider the distance r_{min} that would just meet the signal to interference criteria for an interferer on the same channel. In this case (with obvious notation):

$$\frac{P_{sig}}{P_{\text{int}}} = \frac{Kr_{\min}^b}{g_{UL}^{\max} g_L^{\max} P_{UL}^{\max} R_B^a} = T_S$$

[31] If two different unlicensed devices disrupt the same licensed device it counts a two licensed devices disrupted.

$$r_{\min} = \left(\frac{g_{UL}^{\max} g_L^{\max} P_{UL}^{\max} R_B^a T_S}{K} \right)^{1/b}$$

Combining these results we get

$$D = \pi \frac{N_L N_{UL}}{A} r_{\min}^2 \left(\frac{g_{UL}}{g_{UL}^{\max}} \frac{g_L}{g_L^{\max}} \frac{P_{UL}}{P_{UL}^{\max}} \frac{T}{T_S} \right)^{2/b} \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}} .$$

There are four final random variables that need to be considered: the distribution of the unlicensed and licensed antenna gains; the distribution of unlicensed power levels; and the distribution of device thresholds. These are assumed to be independent of each other and the other random variables.

The unlicensed antenna has an antenna pattern, $g_{UL}(\theta)$. The expected contribution to the number of disrupted receivers is:

$$\int_0^{2\pi} \left(g_{UL}(\theta)\right)^{2/b} p_{g_{UL}}(\theta) d\theta = \frac{1}{2\pi} \int_0^{2\pi} \left(g_{UL}(\theta)\right)^{2/b} d\theta$$

where the distribution $p_{g_{UL}}$ is assumed to be uniform.[32] Define

$$G_{UL} = \frac{1}{2\pi} \int_0^{2\pi} \left(\frac{g_{UL}(\theta)}{g_{UL}^{\max}} \right)^{2/b} d\theta$$

Typical values are

$G_{UL} = 1$ if the antenna is omnidirectional

$G_{UL} = w/360$ if the antenna is an ideal sectorized antenna of width w in degrees.

Similarly we define the licensed antenna gain factor:

$$G_L = \frac{1}{2\pi} \int_0^{2\pi} \left(\frac{g_L(\theta)}{g_L^{\max}} \right)^{2/b} d\theta$$

Power control would result in a distribution of power levels. Similar to the antenna gains we define the power control gain factor:

$$P = \int_0^{P_{UL}^{\max}} \left(\frac{P_{UL}(x)}{P_{UL}^{\max}} \right)^{2/b} p_{P_{UL}}(x) dx .$$

where $p_{P_{UL}}$ is the distribution of power levels. Example values are

$P = 1$ when the unlicensed device always transmits at maximum power

$P = b/(b+2)$ if power is uniform between 0 and $P_{UL}^{\max}$.

[32] A receiver detection technique might lead to null steering or other techniques so that the antenna angle distribution would not be uniform.

$$P = \frac{b}{2}\frac{1-\left(P_{UL}^{\min}/P_{UL}^{\max}\right)^{2/b}}{\ln P_{UL}^{\max}/P_{UL}^{\min}}$$ if $\ln P_{UL}$ is uniform between $\ln P_{UL}^{\min}$ and $\ln P_{UL}^{\max}$ (i.e. it is uniform in dB between the min power in dB and the max power in dB).

The distribution of required thresholds depends on the likelihood of choosing the same channel, or one of the neighboring channels, or more separated channels. Even if the unlicensed device is working on a channel far removed from the channel used by the licensed device, a sufficiently strong signal can overwhelm the receiver. So, all channels must be considered. Therefore we define:

$$C = \sum_i p_i \left(T_i/T_S\right)^{2/b}$$

where if N is the channel used at a licensed receiver, p_i is the probability of the unlicensed device being on channel $N + i$, and T_i is the threshold required in this case. For instance, for DTV[33]

I	T_i/T_s(dB)
0	0.0
+/–1	48.5
+/–2	74.2
+/–3	78.2
+/–4	84.2
+/–5	86.2
+/–6	80.2
+/–7	87.2
$\|i\|>7$	90.2

As a worst case example, let the channels be chosen randomly and we ignore channel edge effects. Then

C = 0.020 if b = 2

C = 0.020 if b = 4

If the unlicensed radio avoids the same and adjacent channels of the licensed receiver (i.e. is at worst at N +/– 2) then at worst:

$C = 3.8\text{x}10^{-8}$ if b = 2

$C = 2.0\text{x}10^{-4}$ if b = 4

If the unlicensed radio can always avoid any channel within +/– 7 of a receiver channel, then

$C = 9.6\text{x}10^{-10}$ if b = 2

$C = 3.1\text{x}10^{-5}$ if b = 4

We let all the model factors be denoted by M

[33] ATSC A-74 *DTV Receiver Performance Guidelines*

$$M = \pi \frac{b}{b+a} e^{\frac{2\sigma^2}{b^2}}$$

Then

$M =$ 5.8 if $a = 2$, $b = 2$, and $\sigma = 7$dB

$M =$ 2.9 if $a = 2$, $b = 4$, and $\sigma = 7$dB

Licensed receivers or unlicensed transmitters may simply be turned off and not part of creating of causing interference. A licensed receiver may be receiving its signal via cable and not through over-the-air broadcasts. The last factor captures the fraction of devices eligible to participate in the device interaction:

$$E = F_{ONUL}\, F_{ONL}\, F_{BC}$$

Where F_{ONUL} is the fraction of the unlicensed devices that are turned on at any time, F_{ONL} is the fraction of licensed receivers that are on, and F_{BC} is the fraction of receivers that listen to over-the-air broadcasts as opposed to cable TV.

Putting all these factors together and noting $F = D / N_L$ yields the main result:

$$F = r_{\min}^2 PCEG_{UL} G_L M N_{UL} / A$$